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14. ABSTRACT

The UMD Workshop on Distributed Sensing, Actuation, and Control for Bio-inspired Soft Robotics was held at the University of Maryland, College Park, MD, on September 11-12, 2014. The workshop brought together 40 scientists, mathematicians, and engineers from a range of STEM disciplines (e.g., neurobiology, applied mathematics, and control theory) for discussions on the fundamental challenges of distributed sensing, actuation, and control of hyperelastic continue. The workshop lasted one full day and one half day and included a combination

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Final Report: UMD Workshop on Distributed Sensing, Actuation, and Control for Bio-inspired Soft Robotics

ABSTRACT

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

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Number of Papers published in non peer-reviewed journals:

(c) Presentations

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received   Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received   Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received   Paper

TOTAL:

Number of Manuscripts:

Books

<u>Received</u>   <u>Book</u>

  TOTAL:

<u>Received</u>   <u>Book Chapter</u>

  TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Derek Paley	0.00	
Norman Wereley	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

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Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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Names of Personnel receiving masters degrees

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Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

UMD Workshop on Distributed Sensing, Actuation, and Control

for Bio-inspired Soft Robotics

Final Report to ONR & ARO from Workshop Program Committee

1 October 2014

The UMD Workshop on Distributed Sensing, Actuation, and Control for Bio-inspired Soft Robotics was held at the University of Maryland, College Park, MD, on September 11-12, 2014. *The workshop brought together 40 scientists, mathematicians, and engineers* from a range of STEM disciplines (e.g., neurobiology, applied mathematics, and control theory) for discussions on the fundamental challenges of distributed sensing, actuation, and control of hyperelastic continua. The workshop lasted one full day and one half day and included a combination of short talks, five breakout discussions, and a social event. The workshop emphasized working discussions on the cutting-edge open research questions – rather than research presentations on the state-of-the-art. In addition to this report, a subset of the workshop participants plan to submit articles to a special issue of the Bioinspiration & Biomimetics journal on the topic of *Bioinspired Soft Robotics.* It was evident from the workshop that MURI-worthy challenges and opportunities currently exist in the areas of distributed sensing, actuation, and control for bio-inspired soft robotics due to recent advancements in smart materials and 3D printing. The following is a summary of the breakout sessions and the group discussions that followed each session.

Workshop participants identified a need for *unification and standardization*, including model systems and testbeds. (Indeed restricting the scope of the problem may unleash creativity.) A McMaster-Carr for soft materials would address the existing problems in material supply. For example, polyurethane used in stretchable electronics is sold in units of tons, whereas most research purposes would need much smaller amounts. Also, companies such as 3M frequently change the recipes for materials, resulting in varying properties. A data sheet for properties of soft materials, including washability, would be useful. However, since softness depends on the length scale, what are the equivalent nondimensional Reynolds-type numbers for soft materials? There was also a discussion of developing a *grand challenge* environment, which has precedence in other fields (ROS, ATLAS). A soft-robotics kit that anyone can download an use would help advance soft robotics education (e.g., soft Legos). Ground rules for a soft robotics grand challenge should include constraints on price, energy, and structural constraints. Proposed tasks include object manipulation, locomotion, and exploration using tactile sensing.

Research in soft robotics will impact a variety of research fields in science and engineering and *has the potential to impact a wide set of applications in areas of societal need*. For example, control theory and control engineering with distributed, multimodal, and adaptive sensors, actuators, energy sources, and materials could suggest new canonical plant models with complex spatiotemporal characteristics. The ability to mass produce soft robots could provide incentive to the machine-learning community to tackle complex dynamical systems (rather than

the current focus, which is information driven). Other fields potentially impacted include: tissue engineering/biology (incorporating tissues, cells into soft robotics, conversion of tissue engineering with soft robotics); ethics (public opinion, policy); engineering (control aspects, mobility, sensors, fluid dynamics, interface with electronics); additive manufacturing (new fabrication tools); biomedical engineering (intelligent drug design and delivery); and medical devices (soft surgical tools). Indeed a *wide array of relevant Naval problems* were identified for underwater and aerial vehicles, including vehicles that are efficient, stealthy, highly maneuverable and capable of long duration missions; UUVs that can operate in shallow water, surf zone, strong currents; the derivation of energy from turbulent flows; non-magnetic propulsion for vehicles; sensing for obstacle avoidance; reversible adhesion to hulls; vehicles that can operate at great depths; movable sensor fields; manipulation for EOD (precision positioning, removal/emplacement, pull and twist); compliant robots/vehicles/arms for less hazardous operation close to humans; bio-inspired wings, bodies, and control surfaces; ability to survive contact with obstacles; and the ability to transition between operating air and water.

The following is a focused multidisciplinary research agenda topic with definable goals and outcomes that can be achieved in 3–5 years.

Background: Robotics research is transforming under the influence of smart materials, flexible electronics, 3D printing, and bio-inspired designs. Indeed, the suite of tools available to engineers, scientists, and biologists now enables the creation of soft(er) robotics that better emulate the diverse capabilities of flexible appendages of living organisms in order to accomplish tasks that rigid robots cannot. But many open challenges and questions exist -- even the notion of softness is scale dependent. Nonetheless, there has emerged a vision in which novel materials are used to fabricate smart functional units to be combined into a useful working system capable of recruiting sensing and/or actuation resources on demand and mechanically learning its responses to environmental stresses. This vision may incorporate four-dimensional printing in which three-dimensional mechanisms are fabricated out of physically or chemically reactive or even living materials. Its bioinspiration stems from a comparative rather than an extreme perspective -- how do organisms achieve distributed computing, sensing, actuation, and power? Flexible, controlled structures are ubiquitous in the natural world, ranging from squid, jellyfish, and sea stars in the marine environment to elephant trunks in the terrestrial domain. However, emulating biological sensing and actuation with multi-functional materials is desired but not sufficient without closed-loop control. A key goal is how to extend what is possible using smart materials by designing complex structures and dynamical controllers. Traditional control frameworks with distinct sensing, actuation and control blocks fail to describe the potential of multi-functional materials in which sensors and actuators are integrated and noisy. Modeling the dynamics, large strains, and flexibility of soft, continuous structures may require continuum mechanics and possibly non-Newtonian physics of granular materials.

Objective: A fundamental understanding of the role of dynamics and control in soft structures and in particular robotic systems fabricated from smart, flexible materials. A principled approach to the modeling and design of bioinspired flexible structures and appendages.

Research Concentration Areas:

- Distributed architectures that exploit biological strategies, including local sensing, feedback control, and muscle-like actuators, in order to achieve motion primitives
- Concentration on relevant problems in autonomous robotics based on soft designs like muscular hydrostats in aquatic, terrestrial, and/or aerial environments
- A control theoretic abstraction of the neuromechanics that leverages the intrinsic dynamics of an infinite-dimensional system
- Extending the performance capabilities of materials using novel structures in order to distribute the sensing and controls between morphology and sensor processing

Another outcome of the workshop was the fostering of a network of researchers with overlapping interests in bioinspired soft robotics. Indeed, there was discussion of replicating the workshop on an annual or biannual basis. Some participants expressed interest in organizing a special session/track at a suitable robotics and controls conference like ICRA, IROS, CDC, or ACC.

	Participant	Institution	Field
1	Aimy Wissa	University of Illinois at Urbana-Champaign	Aerospace Engineering
2	Derek Paley	University of Maryland	Aerospace Engineering
3	James Hubbard	University of Maryland	Aerospace Engineering
4	Norm Wereley	University of Maryland	Aerospace Engineering
5	Feitian Zhang	University of Maryland	Aerospace Engineering
6	Nanshu Lu	University of Texas at Austin	Aerospace Engineering
7	Iain Anderson	University of Auckland	Bioengineering
8	Anders Garm	Lund University	Biology
9	Eric Tytell	Tufts University	Biology
10	Shai Revzen	Michigan University	Biology
11	Dan Speiser	University of South Carolina	Biology
12	Barry Trimmer	Tufts University	Biology
13	David Gracias	Johns Hopkins	Chemical Engineering
14	Marc in het Panhuis	University of Wollongong	Chemical Engineering
15	Nikolaus Correll	University of Colorado Boulder	Computer Science
16	Josh Bongard	University of Vermont	Computer Science
17	Timothy Horiuchi	University of Maryland	Electrical Engineering
18	Xiaobo Tan	Michigan State University	Electrical Engineering
19	Thomas Löher	Technical University of Berlin	Electrical Engineering
20	Qibing Pei	University of California, Los Angeles	Material Science
21	Hugh Bruck	University of Maryland	Mechanical Engineering
22	Kamran Mohseni	University of Florida	Mechanical Engineering
23	Kwang Kim	University of Nevada, Las Vegas	Mechanical Engineering
24	Christopher Kroninger	Army Research Laboratory	Mechanical Engineering
25	Robert Shepherd	Cornell University	Mechanical Engineering
26	Kathryn Daltorio	Case Western Reserve University	Mechanical Engineering
27	SK Gupta	University of Maryland	Mechanical Engineering
28	Elizabeth Smela	University of Maryland	Mechanical Engineering
29	Noah Cowan	Johns Hopkins	Mechanical Engineering
30	David Hu	Georgia Tech	Mechanical Engineering
31	Dan Goldman	Georgia Tech	Physics
32	Geoff Slipher	Army Research Office	Program Manager
33	Samuel Stanton	Army Research Office	Program Manager
34	Massimo Ruzzene	National Science Foundation	Program Manager
35	Tom McKenna	Office of Naval Research	Program Manager